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# OBSERVATIONS OF FLUORINE NUCLEI IN THE PRIMARY COSMIC RADIATION MADE ON THE PIONEER 8 SPACECRAFT

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COSMIC RAY GROUP

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ABSTRACT

Measurements with a counter telescope aboard the Pioneer 8 spacecraft have identified fluorine nuclei in the primary cosmic radiation. The fluorine abundance is 1-2% of oxygen in the energy range above 500 MeV/nuc. This abundance is consistent with a fragmentation origin for these nuclei resulting from the passage of heavier cosmic rays through $\sim 4$ g/cm$^2$ of hydrogen.

It is generally argued that cosmic ray particles have passed through $\sim 4$ g/cm$^2$ of material before we observe them here at earth. This is consistent with the production of the appreciable amount of Li, Be and B nuclei that is observed. The abundances of other secondary fragmentation nuclei such as $H^2$, $He^3$ also seem to be consistent with such a path length. Recently Fan, Gloeckler and Simpson (1968) have reported a value $\leq 1.4 \times 10^{-3}$ for the fluorine to oxygen ratio in the energy interval 50-120 MeV/nuc. These authors and others have pointed out that this small abundance of fluorine is difficult to reconcile with the passage of cosmic rays (in particular the principal progenitors of F, the Ne, Mg and Si nuclei) through anything like 4 g/cm$^2$ matter. Unfortunately the cross sections for the production of fluorine can only be crudely estimated. Certainly the above experimental limit suggests a path length $\lesssim$ 0.5 g/cm$^2$ according to our current knowledge of the appropriate nuclear spallation cross sections.

This observation has led both the above authors and Burbidge, Fowler and Hoyle (1967) to consider "two component" models for the origin of cosmic rays. Fichtel and Reames (1969) have recently evaluated the cosmic ray propagation problem in considerable detail and conclude that, using our current understanding of the nuclear spallation cross sections, the two component models as formulated above do not lead to predictions consistent with <u>all</u> of the known experimental abundances. They point out that the one measurement of the F/O ratio seems to be irreconcilable with all contemporary models for the origin and propagation of cosmic rays.

The measurement of fluorine nuclei, lying between the much more abundant oxygen and neon nuclei, is an experimental accomplishment requiring charge resolution of the highest order. In addition to the satellite measurement of Fan et al. (1968), earlier emulsion measurements of the fluorine abundance at balloon altitutdes are summarized by Kristiansson (1966). These suggest a F/O ratio $\lesssim$ 0.1 at a few g/cm$^2$ depth in the atmosphere at energies above a few hundred MeV/nuc. The counter measurements of Webber and Ormes (1967) place an upper limit $\sim$ 0.05 on this ratio at $\sim$ 4 g/cm$^2$ atmospheric depth.

The ratios obtained at balloon altitudes are obviously limited by the charge resolution of the instruments used. They also represent an upper limit to the ratio in interplanetary space because of the production of fluorine in the residual atmosphere.

In this paper we shall report observations of a finite fluorine abundance in the energy range > 500 MeV/nuc obtained with a counter telescope aboard the Pioneer 8 satellite.

The detector system used is shown in Figure 1. It is a 6 element solid state-Cerenkov telescope. A technique is used whereby the minimum pulse from 3 solid state detectors $B_1$, $B_2$ and $B_3$ are selected. This significantly improves resolution over more conventional systems. The use of a Cerenkov detector in the two dimensional pulse height representation extends the energy range to relativistic energies and also provides directional information.

The ultimate usefulness of any detector system for studying the chemical composition of cosmic rays and particularly for identifying a rare species such as flourine depends on the intrinsic resolution. In Figure 2 we show a pulse height matrix covering the charge range Z = 6-10 from $\sim$ 50 days observing time. This is selected from the high energy matrix (Cerenkov output > 0) and displays the spectrum from $\sim$ 300 MeV/nuc upwards in energy. The density of events along a given "charge line" can be used to obtain the differential spectrum in the range 350-1500 MeV/nuc and the integral intensity of higher energy particles. The presence of fluorine nuclei is unmistakable. This is further established by constructing pulse height histograms by making cuts perpendicular to each charge line. Histograms showing the presence of fluorine nuclei in various energy intervals are shown in Figure 3. In $\sim$ 50 days observing time approximately 50 of these nuclei have been recorded above $\sim$ 500 MeV/nuc. During the same time period $\sim$ 2,200 oxygen nuclei were detected. The average F/O ratio is thus roughly $2 \times 10^{-2}$ = 2% or $\sim$ 10 times that observed by Fan et al. (1968) at $\lesssim$ 100 MeV/nuc.

A crude estimate of the contribution to the observed fluorine arising from the production of secondary fluorine within the experiment telescope has been made. The few measured spallation cross sections for the production of fluorine in hydrogen have been geometrically extrapolated to spallation cross sections for the production of fluorine in silicon and copper. It should be noted that the interaction mean free paths for the principal progenitor nuclei, Ne, Mg and Si, are $\sim$ 5 g/cm$^2$ in hydrogen and $\sim$ 40 g/cm$^2$ in copper therefore the effects of fragmentation in the telescope are much reduced over an equivalent amount of hydrogen. The calculation gives a secondary contribution of < 10% of the observed fluorine. Thus the (dominant) fraction of the fluorine we observe must be present in the galactic radiation.

It is possible to examine the F/O ratio as a function of energy by unfolding the energy spectrum of these nuclei from the pulse height distribution. The F and O differential spectra as well as the F/O ratio which we derive above 500 MeV/nuc are presented in Figure 4. The points at $\sim$ 5 BeV/nuc are obtained from the integral intensity points > 2 BeV/nuc by assuming differential spectra $\sim E_T^{-2.5}$. The Pioneer 8 F/O ratio is always larger than that observed by Fan et al. (1968) at lower energies; however, because the two sets of measurements do not actually overlap in energy it is not necessarily obvious that they are contradictory.

We shall now try and relate this measurement with the hypothesis that fluorine is created as secondaries from the fragmentation of heavier nuclei - principally Ne, Mg, Si in hydrogen. We have already indicated that the relevant fragmentation parameters can be only crudely estimated so the resulting conclusions must necessarily be limited. The sole constituant of cosmic ray fluorine must be $F^{19}$ since this is the only stable isotope. The cross sections for reactions leading to $F^{18}$ are the only ones measured to date, however cross sections leading to $F^{19}$ should be expected to be similar (Burbidge, et al., 1967). The available cross sections to $F^{18}$ summarized by Fichtel and Reames, (1969) and Cowsik et al., (1967) give a F/O ratio = 0.5% per g/cm$^2$ of hydrogen at an energy of approximately 150 MeV. About 60% of this fluorine is supplied by interactions of Ne which has a cross section for production of fluorine of $\sim$ 30 mb at this energy. On the basis of the behaviour of other analogous one nucleon stripping cross sections with energy (eg $C^{12}(p, pn)B^{11}$) the F./O ratio would be expected to be somewhat less at higher energies.

The observed F./O ratio is thus consistent with the passage of heavier cosmic rays through $\sim$ 4 g/cm$^2$ of material in agreement with the current interpretation of the abundance of Li, Be and B nuclei. Our conclusion must therefore necessarily be different than that of Fan et al., (1968) in this regard although as pointed out earlier since the measurements do not overlap in energy it is not necessarily obvious that they are contradictory. If our observations are taken along with those of the Chicago group they indicate an abrupt decrease in the F/O ratio at low energies. Such a variation is not in accord with our understanding of the variation in fragmentation cross sections for the production of fluorine nuclei with energy.

It should be noted, however, that certain propagational effects can also produce a marked variation of charge ratios with energy. In particular the exponential path length distribution model of Cowsik et al., (1967) will produce a decrease in the F/O ratio $\sim$ a factor of 4 at low energies even if the fragmentation cross section is taken to be constant with energy. This same model predicts a strong variation of the L/M ratio with energy, however, that is not observed (von Rosenvinge et al., 1969).

Further observations on fluorine and other odd nuclei with charge > 10 are in progress and should help to extend the data reported here.*

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*At the November, 1968 APS meeting in Miami Dr. John Simpson presented a preliminary fluorine measurement from the University of Chicago Imp IV experiment which gives a F/O ratio $\sim 10^{-2}$ at low energies as opposed to the Imp III measurement of $\sim 10^{-3}$ mentioned in the text of this paper. This latest measurement would remove any conflict which may exist between the Minnesota and Chicago fluorine measurements as presented here.

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## Figure Captions

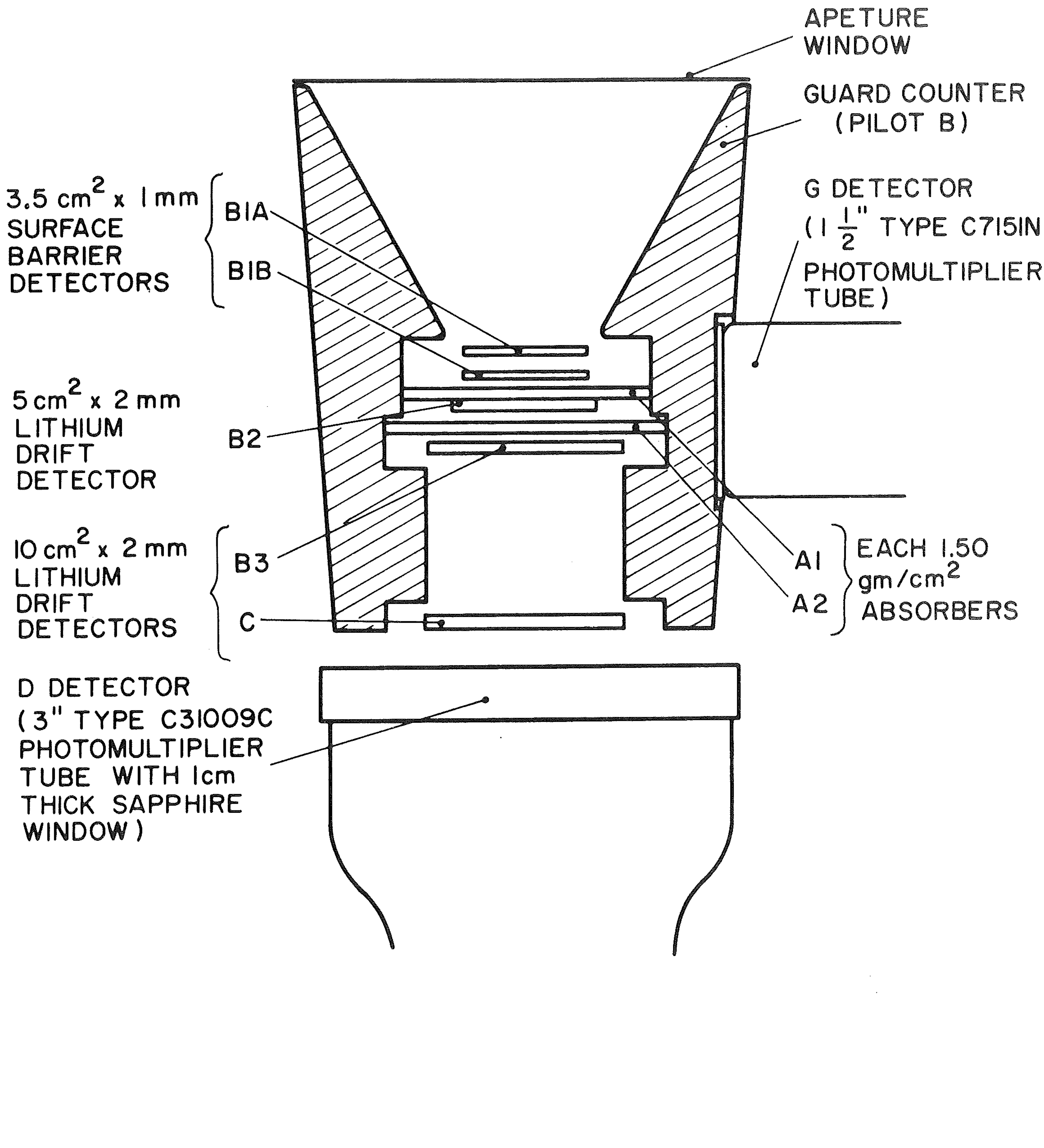
Figure 1 Outline drawing of the cosmic ray telescope in operation on Pioneer 8.

Figure 2 Two dimensional pulse height matrix for the charge range Z = 6-10. Fifty days data (Jan. - Feb., 1968) are used in the compilation. High energies (> 1000 MeV/nuc) lie at the bottom of each charge line, low energies ($\sim$ 200 MeV/nuc) at the top.

Figure 3 Charge histograms for various energy intervals. The expected postition of the flourine nuclei is shown by the arrows.

Figure 4 The differential spectra of flourine and oxygen and the F/O ratio as a function of energy as measured on Pioneer 8. The result of Fan et al., 1968 is shown at low energies.

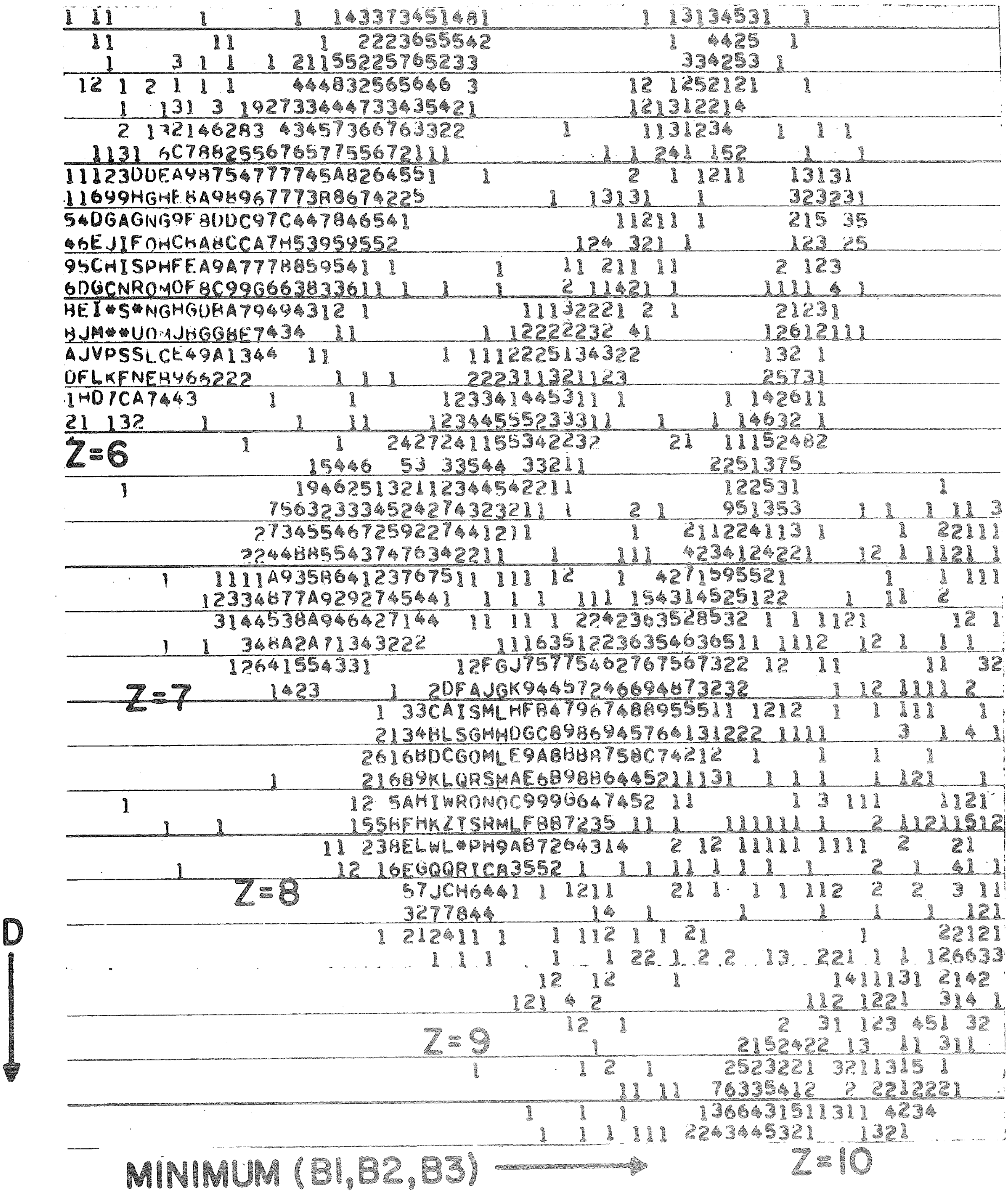
# PIONEER 8
# DETECTOR SYSTEM

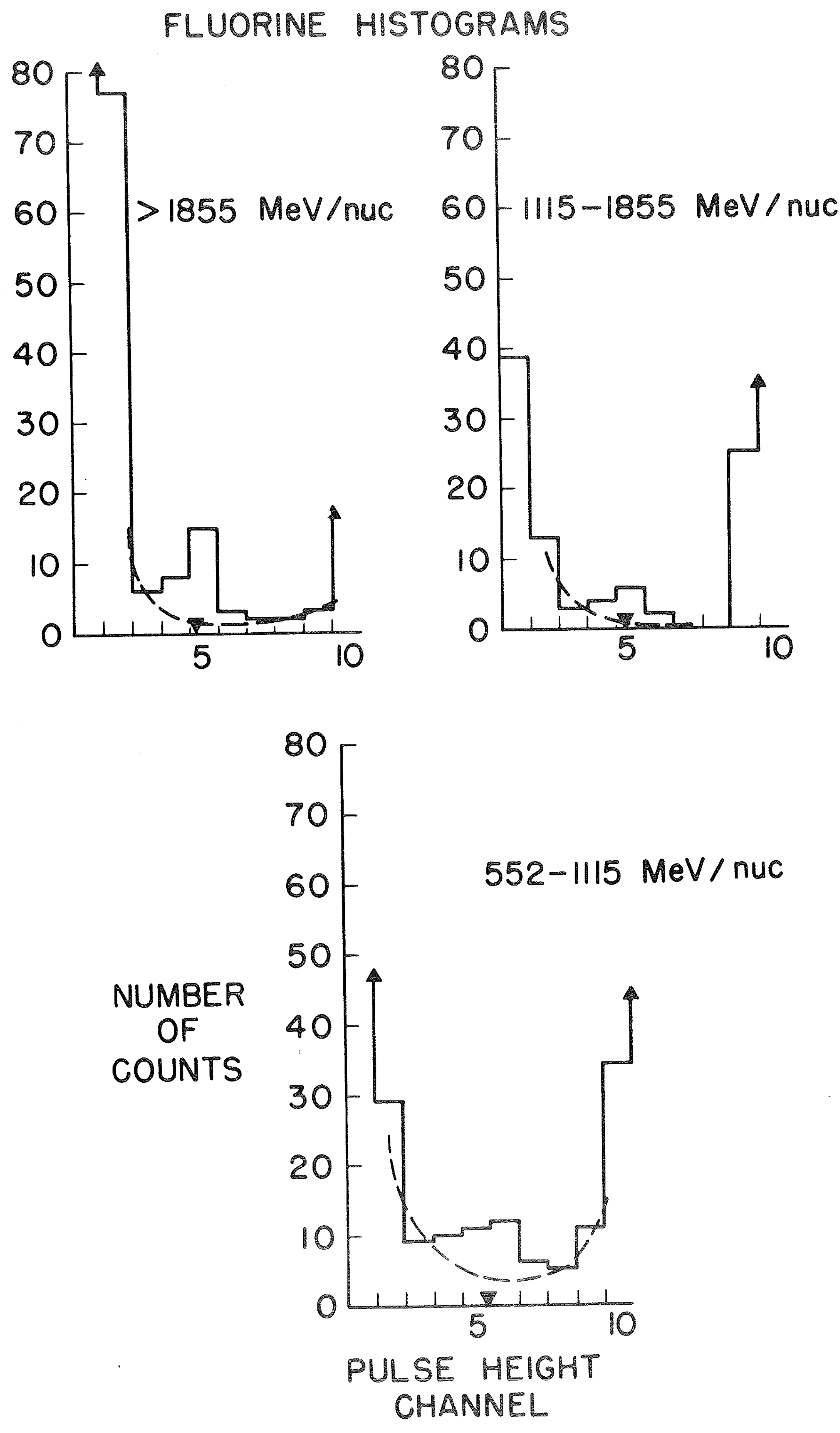


# PIONEER 8

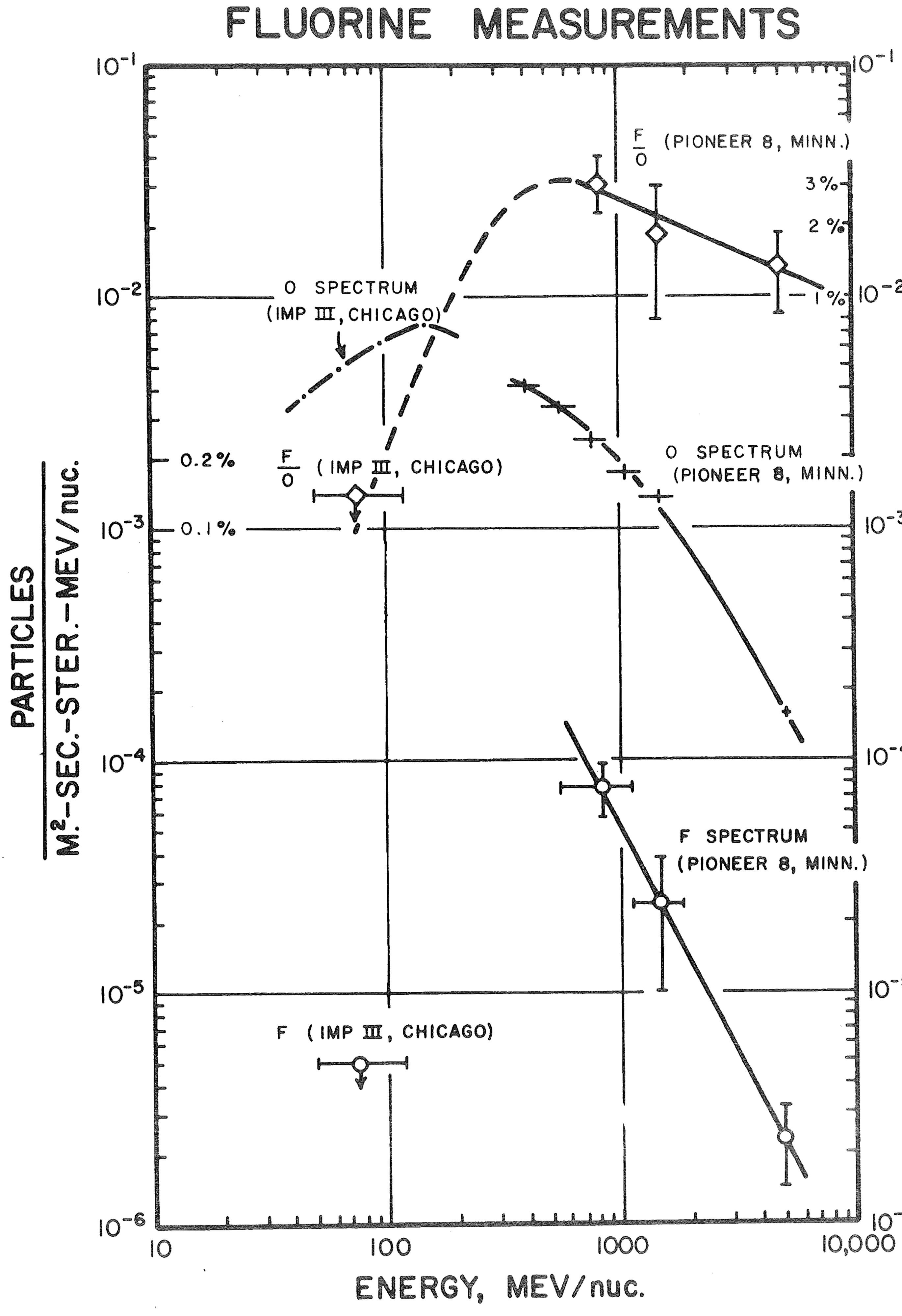
# HIGH ENERGY MATRIX

# (DEC. 21, 1967 — FEB. 8, 1968)





FLUORINE HISTOGRAMS
>1855 MeV/nuc
1115–1855 MeV/nuc
552–1115 MeV/nuc
NUMBER OF COUNTS
PULSE HEIGHT CHANNEL
0
10
20
30
40
50
60
70
80
5
10



FLUORINE MEASUREMENTS
F/O (PIONEER 8, MINN.)
3%
2%
1%
O SPECTRUM
(IMP III, CHICAGO)
0.2%
0.1%
F/O (IMP III, CHICAGO)
O SPECTRUM
(PIONEER 8, MINN.)
F SPECTRUM
(PIONEER 8, MINN.)
F (IMP III, CHICAGO)
PARTICLES / M².-SEC.-STER.-MEV/nuc.
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
10
100
1000
10,000
ENERGY, MEV/nuc.